ЭППТ 2015

ACED 2015

6.1. BATTERY POWERED HIGH EFFICIENCY DRIVE SYSTEMS IN PRACTICAL APPLICATIONS

Helmut Weiss, Dr.techn., Univ.Prof., Montanuniversitaet Leoben, Franz-Josef-Str. 18, 8700 Leoben, Austria. E-mail: helmut.weiss@unileoben.ac.at. Ph.: +4338424022400

Abstract: Since about 30 years three-phase variable speed drives are the standard industrial solution when high reliability, high ingress protection of machine and especially high efficiency are required. Generally, these drives are powered from the grid due to their high power capability. Through Lithium-Ion rechargable batteries, electric variable speed drives for commercial vehicles as cars and trucks become feasible. These Lithium-Ion batteries are no more a completely constant voltage source but vary the voltage mainly dependent on state of charge by about plus and minus 15%. Power electronics for the drive have to cope with this and are strongly influenced by the type of motor, too. Power insertion comes from the grid by special chargers or in case of big mining trucks, by catenaries. Commercial battery powered drives are common between some kW up to 100 kW but are extended up to 800 kW in a heavy truck implementation study.

THREE-PHASE VARIABLE SPEED DRIVES

Three-phase variable speed drives are composed of a synchronous machine or an induction (asynchronous) machine and power electronics including control. State of the art are permanent magnet synchronous machines in cases where very high efficiency and/or low inertia mass are required, and induction machines for drives where lower cost and/or field weakening operation is necessary. Standard power electronics for both cases is the pulse width modulator (PWM) inverter using IGBTs and anti-parallel diodes as switches with switching frequencies between about 3 kHz and 8 kHz. This PWM circuit has a capacitor at its DC side enabling pulse currents produced by switching at this DC side. Generally, the capacitor acts as a very short time power balancer between PMW inverter and DC side power input for motor mode or power output for generator mode. Power is coming over a rectifier from the grid, usually.

MOBILE APPLICATIONS FOR DRIVES

However, as high capacity Lithium-Ion cells have become available we also can use an assemblance of these cells into battery modules and the module interconnected to battery packs as short time power sourde and sink for mobile usage where we do not have catenary power like in railways. First practical electric cars were equipped with lead-acid batteries, then nickel-cadmium batteries and even high temperature batteries like Sodium-Sulphur or Sodium-Nickel-Chloride. By today, power density, life-time and usability of Lithium-Ion batteries provide the best solution for rechargable batteries in off-grid mobile applications. However, even these modern batteries used widely in electrically powered full speed cars have a major constraint: Energy density.

With the best Lithium-Ion batteries we only gain about 4% of the energy content per weight compared to liquid fuel like Diesel. Fuel cells are ten-fold better but limited by Hydrogen storage, peak power, life time, and cost in an even more severe amount.

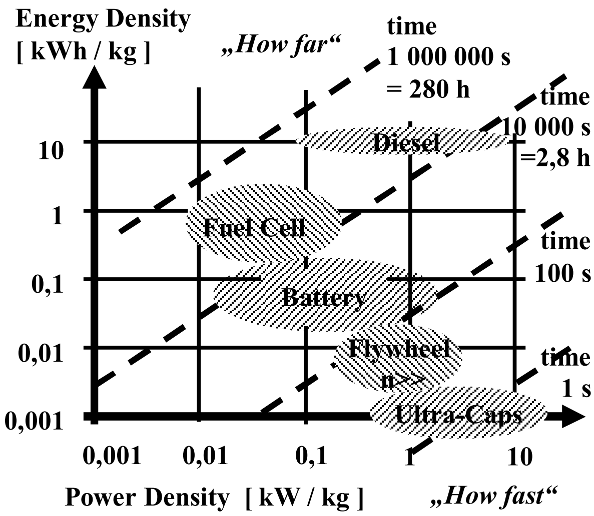

Fig. 1. Energy density and power density relation for standard energy storage media

An overview covering several energy storage media (Fig. 1) reveals that we still lack energy density heavily when using electro-chemical energy storage. For mobile usage we have 2 basic opportunites: Acceptance of limited range before next re-charge despite quite heavy battery stacks or establishing an on-tour battery re-charge arrangement.

VEHICLES WITH BATTERY LIMITED RANGE

Three-phase drive employment rather than DC drives produced a very successful improvement of low power (5 kW) car drive systems like Golf cars. For touristic usage, DC-machine equipped Golf cars were used for passenger transport from valley floor to

500 m sea level difference upwards. The DC machines did not survive this operation as they were designed for flat area operation only. In addition, efficiency was rather poor and so was range of the cars. Implementing PWM inverter fed induction machines and finally Neodymium-Iron-Boron (NdFeB) permanent magnet synchronous machines created troublefree operation capability at steep slopes, too. A final conversion to Lithium-Ion batteries was not realized for cost issues and due to sufficient range of original lead-acid batteries.

A high speed boat drive (80 kW continuous power enabling more than 60 km/h on a lake) again with a special permanent magnet synchronous machine but now water-cooled was developed. The corresponding battery pack had a weight of about 400 kg and the price of the battery was in line with price of boat.

Both drive systems required charging times of more than 10 hours for lead acid batteries and about 1.5 hours for Lithium-Ion batteries.

HEAVY INDUSTRIAL TRUCK DRIVE SYSTEM

In mining applications, huge trucks with total weight of truck and payload up to 400 t are in operation by today. Trucks up to 200 t (including full payload) fully exploit the mechanical limits of mechanical transmission gears to the wheels (Fig. 2).

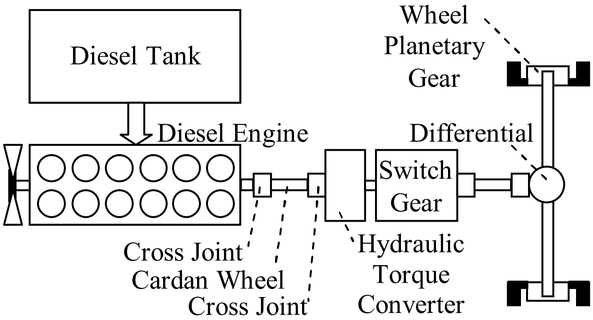

Fig. 2. Drive train for direct Diesel combustion engine power system

With such a system as described in fig. 2 we need the hydaulic torque converter to serve as a special clutch which also provides a gear change opportunity under full mechanical load, and the switch gear to adapt to different torque demands for e.g. slow full load up-slope motion, and fast horizontal motion or fast downhill motion in case the truck is empty. In addition, for braking we have a hydaulic brake system directly attached to the wheels (not shown in Fig. 2).

A more advanced solution has to be found and implemented for heavier systems: Electrical drive system with diesel engine as power source and synchronous generator plus rectifier providing the necessary electrical power followed by a variable speed fully controlled electric drive for each individual wheel of the truck. Today's state of the art for such an electric drive system is a three-phase machine (usually induction machine). The electric section of power train provides a great opportunity in order to reduce the amount of Diesel consumed especially in up-slope motion loaded. Here the electrical drive system receives energy from DC catenaries at the up-slope section of the tour. This DC energy is transmitted into the DC-link of the truck. Only for off-catenaries motion down-slope or for horizontal motion, the diesel engine is powered. However, we have a true hybrid vehicle with the inherent disadvantage of rather heavy equipment providing the two-fold drive capability.

Even for smaller trucks of 100 t payload and less the diesel-electric systems are under development now.

HEAVY INDUSTRIAL TRUCK INNOVATION

A high amount of Diesel is consumed by these Diesel powered heavy trucks as there is no recuperating brake opportunity: Braking energy is simply heat at the very end. Especially at full load down-slope driving we waste a lot of energy. Keeping in mind the cost of fuel (and a little bit also the world-wide CO_2 problem) we want to utilize the energy at breaking operation down-slope, at least some amount for next up-slope motion. We can obtain the braking energy at the electrical side, e.g. at the DC link. Now we need an energy storage system.

Lithium-Ion batteries are available not only in the notebook computer size and module arrangement around 0.1 kWh of energy storage but also (using industrial high capacity cells) for some tens of kWh for electric cars (carrying e.g. 4 passengers) produced by several car manufacturers. Standard cars come to their limits especially due to the weight and cost of such battery packs: Industrial re-chargable Lithium-Ion based batteries are around 10 kg and 1000 EURO per kWh. As about 15 kWh are required for moving such a car at usual speed on highways (e.g. 100 km/h) we obtain a range between 100 km and 250 km at maximum. However, building larger battery packs is no problem. Transport of such a large battery pack is possible provided the payload of the truck accepts it.

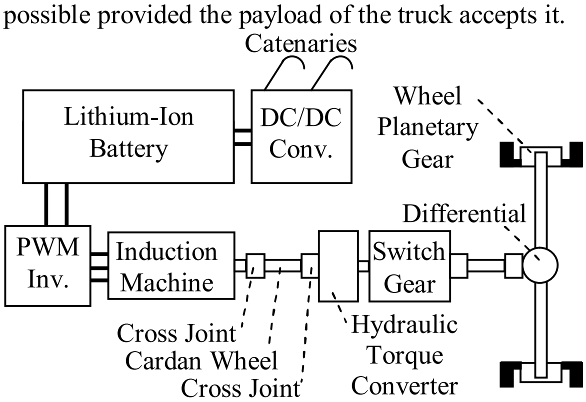

Fig. 3. Drive train for inverter fed induction machine system still using conventional switchgear

A very simple solution is composed of a catenaries electrical power input (as described) and has the diesel engine replaced by an induction machine running at diesel engine speed range while fed over a PWM inverter. The remaining drive train can be the same (Fig. 3). However, such a solution does not exploit all capabilities of electrical drives.

Having a look on the switch gear we identify that generally this gear has to reduce rotational speed of motor and increase torque towards wheel level. The limited operational speed range of diesel engines (speed ration e.g. 1:2) requires several gears including a reverse gear. Electrical machines fed by inverters are inherently able for reverse speed operation as well as operation in the field weaking range providing constant power over a wide range of speed: Exactly the same as it is done in the mechanical way by using switchgear. In addition, a clutch is definitely not necessary as long as the electrical machine covers the required speed range. From these considerations, the system as described in fig. 3 can only be an experimental test vehicle for converting an existing heavy truck to electrical operation under a minimum of mechanical changes.

These considerations finally lead to a simpler solution as described in fig. 4.

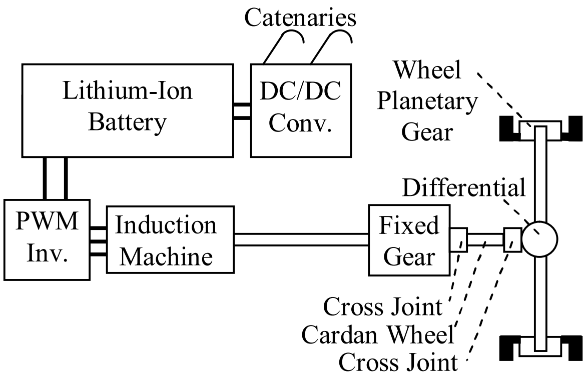

Fig. 4. Drive train for inverter fed induction machine system using wide field weakening range.

Actually, we still have three gear systems in operation:

- Fixed gear in order to reduce the machine rotational speed (e.g. 1000 RPM up to 3000 RPM in field weakening = constant power mode) to differential
- Differential to diverge the input torque to two equal torque outputs (for each driven wheel)
- Wheel planetary gear to further reduce speed onto speed of wheel on tyre and increase torque accordingly.

Differential and wheel planetary gear are decisive components with a given truck series and cannot be changed unless a real new truck is to be developed. Therefore, we concentrate on the opportunities coming from the design variations of an electrical machine.

SELECTION OF ELECTRICAL MACHINE

For reasons of cost, simplicity; and reliability we consider the induction machine as our favorite drive motor and NOT the permanent magnet synchronous machine which has less weight and about half the losses only compared to an equivalent induction machine. Definitely, rare earth magnets are expensive and same is manufacturing due to the active magnets that would collect all nearby iron chips coming from standard manufacturing process. As we need a very wide field weakening range also special (and rather expensive) designs of the rotor of a permanent magnet sysnchronous machine might not fulfill our demands. A decisive point is the behaviour of the machine and converter system in case of overcurrent.

With an induction mache, the standard and simple and nicely working option to survive overcurrents is to simply block all pulses. Current is automatically reducing itself over the free-wheeling diodes of the PWM inverter circuit.

A permanent magnet synchronous machine must be set into the field weakening range by introducing a corresponding direct axis stator current reducing the field so that the stator voltage applied by the PWM inverter is the correct one for this over-excited point of operation. In case that the current goes out of control it becomes necessary to keep on pulsing in order to avoid that the full magnetic field drives a huge overcurrent over the free-wheeling diodes of the PWM inverter circuit. A solution is maybe applying a short circuit to the machine terminals. However, we might get problems due to the excessive currents creating peak torques damaging the mechanical system or demagnetizing some rotor magnets.

In order to obtain a very wide field weakening range (we need 1:3 for our system) we have to design the machine onto small leakage inductances. This design feature - on the other hand - produces high rates of di/dt in the stator currents. Along with this effect we also will get high pulsating torque amplitudes.

Countermeasures can be a high pulse frequency (actually limited by losses in semiconductors) or converter designs with better voltage waveform, e.g. three-level-inverters.

Taking the relatively slow fixed gear side output speed equal to differential input speed into account we also have the opportunity to design a torque motor, i.e. a machine running in a rather low speed range. Direct drives using this principle employ synchronous machines usually, and then permanent magnet synchronous machines. It might be a really demanding work to design a low speed high torque induction machine still providing a reasonable power factor and efficiency. This machine will be much larger and heavier than the previous one, but we have removed the mechanical fixed gear, too. An electrically excited synchronous machine might be an interesting alternative. Eventually, we yield a solution as displayed in fig. 5.

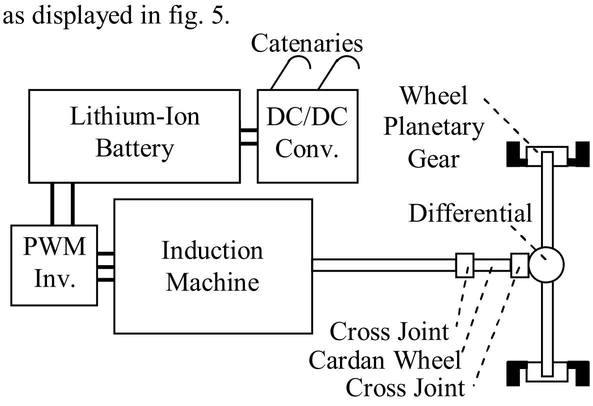

Fig. 5. Drive train for inverter fed induction machine system using wide field weakening range and driving directly the differential gear.

Further developments omitting the differential and employing seperately driven wheels (one induction machine per wheel) are possible but will create an absolutely new truck design.

BATTERY PROPERTIES TO BE HANDLED

Standard electrical AC drives are usually fed over PWM inverters connected to a constant voltage DC source. Unfortunately, the voltage of a battery changes with state of charge. For standard Nickel-Cobaltum-Manganium cathode Lithium-Ion batteries, we start at 4.2 Volts per cell fully charged, drop to about 3.6 Volts when moving through 50% state of charge and ending up at 3.0 Volts at 0% state of charge finally. This 100% full cycle is NOT favourable for usual operation. For a given battery, such a 100% full cycle will yield e.g. 1000 cycles until the battery is to be replaced. A derating of the used capacity compared tom the rated 100% capacity is highly recommended: Exploiting only 90% of rated capacity shall yield 3000 cycles. Using derating we also reduce the voltage variation at the DC link.

CONCLUSION

Lithium-Ion battery operated drives of high power (e.g. 800 kW) use energy storage capability (e.g. 400 kWh) and are recharged during up-slope driving by means of catenaries. Although the battery module might get a mass of e.g. 5 t for this 400 kWh storage, a heavy truck with 100 t payload can handle such load. Fig. 6 demonstrates the advantage of such a recuperation system.

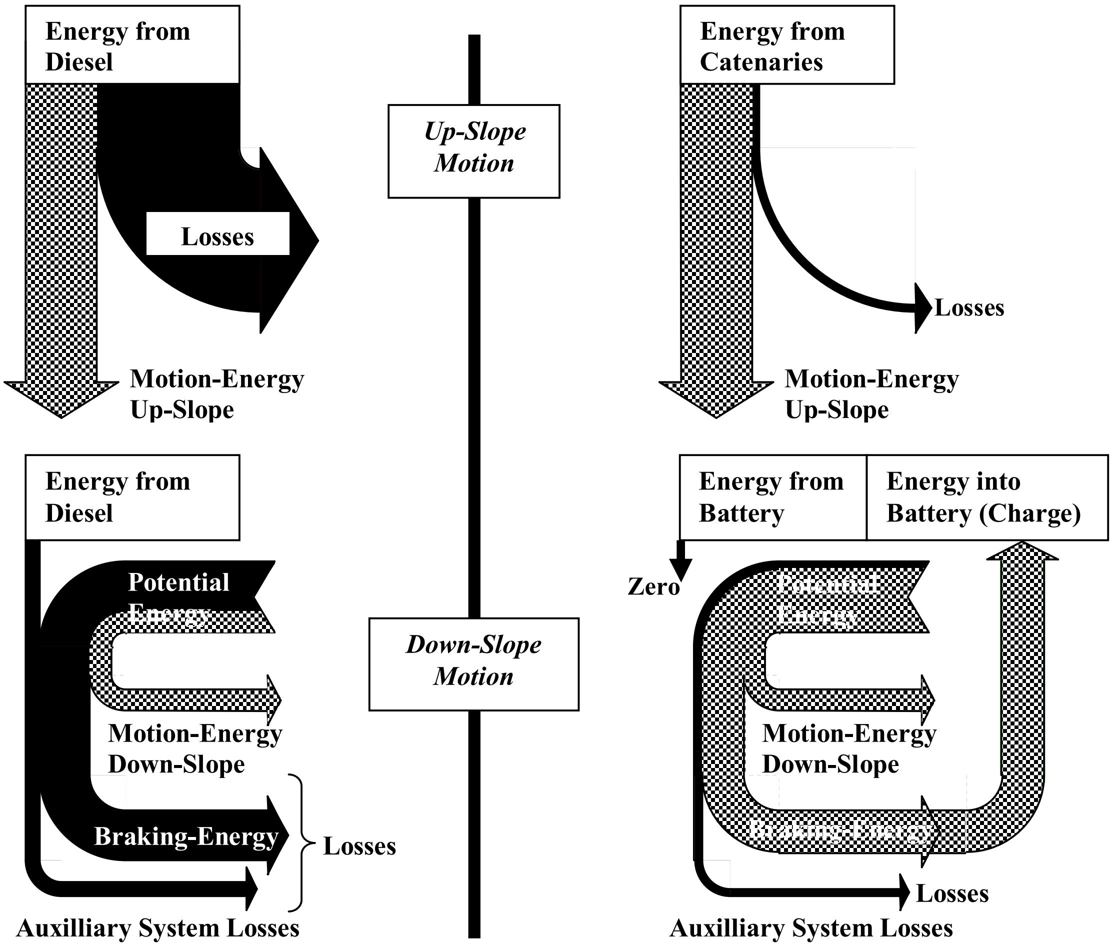

Fig. 6. Energy considerations for Diesel and catenaries/battery power up-slope and down-slope